Primer on Mixed-Mode Transformations in Differential Interconnects

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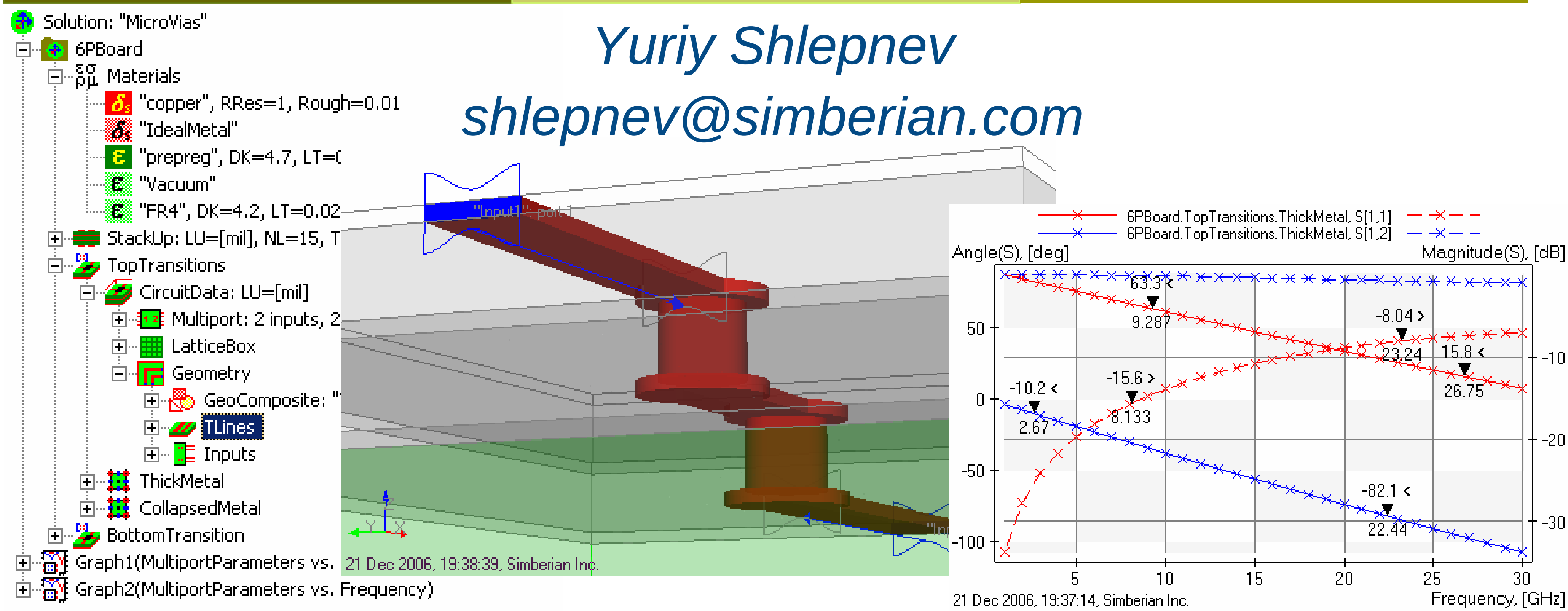


Agenda

- Introduction
- Mixed-mode transformations and geometrical symmetry
- Double micro-strip line bend
- Investigation of micro-strip channel with two reversed bends in frequency and time domain
- Experimental validation
- Possible ways to minimize the mode transformation
- Conclusion

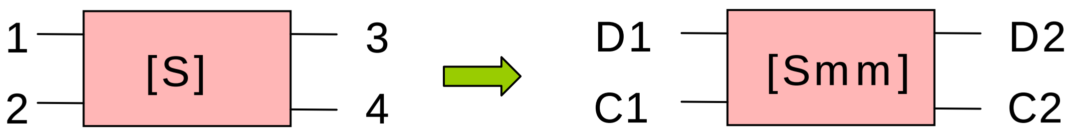
Introduction

- Transformation from differential to common modes is unwanted effect in differential interconnects
  - Common mode may cause differential signal degradation (skew) and electromagnetic emission
- Transformation usually takes place at bends and non-symmetrical routing near via-holes
- The most accurate way to quantify the effect is in the frequency domain with S-parameters in the mixed-mode space
- In case of bends the transformation effect can be simulated with the local electromagnetic analysis
- This presentation contains some practical observations on the estimation and minimization of the mode transformation effect
- Experimental validation provided by Teraspeed Consulting Group
- Simbeor 2008 software has been used for all computations

Mode transformation in reciprocal 4-port

- See details in D.E. Bockelman, W.R. Eisenstadt, Combined differential and common-mode scattering parameters: Theory and simulation, IEEE Trans. on MTT, vol. 43, 1995, N7, p. 1530-1539

Terminal space | Mixed-mode space



$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{bmatrix}$$

$$Smm = \begin{bmatrix} S_{D1,D1} & S_{D1,D2} & S_{D1,C1} & S_{D1,C2} \\ S_{D1,D2} & S_{D2,D2} & S_{D2,C1} & S_{D2,C2} \\ S_{D1,C1} & S_{D2,C1} & S_{C1,C1} & S_{C1,C2} \\ S_{D1,C2} & S_{D2,C2} & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

$$Smm = T \cdot S \cdot T^t$$ - congruent transformation preserves matrix symmetry

$$T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

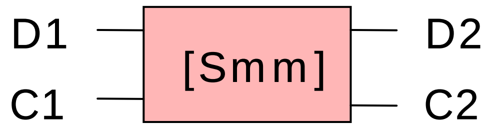
Mode Transformation Terms:

$$S_{D1,C1} = 0.5 \cdot \left(S_{1,1} - S_{2,2} \right)$$
$$S_{D1,C2} = 0.5 \cdot \left(S_{1,3} - S_{2,3} + S_{1,4} - S_{2,4} \right)$$
$$S_{D2,C1} = 0.5 \cdot \left(S_{1,3} - S_{1,4} + S_{2,3} - S_{2,4} \right)$$
$$S_{D2,C2} = 0.5 \cdot \left(S_{3,3} - S_{4,4} \right)$$

All S-matrices are symmetrical (S[i,j]=S[j,i]) due to reciprocity property (if only isotropic materials used to manufacture interconnects)

Mixed-Mode Terminology

- Block DC describes modal transformations or conversion (highlighted blocks of the mixed-mode S-parameters)



Notation used here:

$$Smm = \begin{bmatrix} S_{D1,D1} & S_{D1,D2} & S_{D1,C1} & S_{D1,C2} \\ S_{D1,D2} & S_{D2,D2} & S_{D2,C1} & S_{D2,C2} \\ S_{D1,C1} & S_{D2,C1} & S_{C1,C1} & S_{C1,C2} \\ S_{D1,C2} & S_{D2,C2} & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

Alternative forms:

$$Smm = \begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD12} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{DC11} & S_{DC21} & S_{CC11} & S_{CC12} \\ S_{DC12} & S_{DC22} & S_{CC12} & S_{CC22} \end{bmatrix}$$

$$Smm = \begin{bmatrix} S^{dd}_{1,1} & S^{dd}_{1,2} & S^{dc}_{1,1} & S^{dc}_{1,2} \\ S^{dd}_{1,2} & S^{dd}_{2,2} & S^{dc}_{2,1} & S^{dc}_{2,2} \\ S^{dc}_{1,1} & S^{dc}_{2,1} & S^{cc}_{1,1} & S^{cc}_{1,2} \\ S^{dc}_{1,2} & S^{dc}_{2,2} & S^{cc}_{1,2} & S^{cc}_{2,2} \end{bmatrix}$$

S[D1,C1], S[D2,C2] – **Near end mode transformation** or transformation from differential to common mode at the same side of the multiport

S[D1,C2], S[D2,C1] – **Far end mode transformation** or transformation from differential mode on one side to the common mode on the opposite side of the multiport

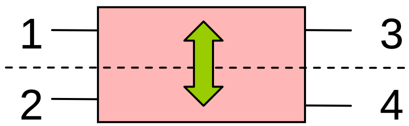
Transformation from common to differential is exactly the same due to reciprocity (symmetrical S-matrix)

Properties of S-parameters of reciprocal 4-port with geometrical mirror symmetry

- Group theory can be used to investigate properties of S-matrix a 4-port with geometrical symmetry – see details in R.H. Dicke - Symmetry of waveguide junctions, in Montgomery, Dicke, Purcell, Principles of Microwave Circuits, 1964

S-matrix of reciprocal 4-port is symmetric as shown below (S[i,j]=S[j,i]):

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{bmatrix}$$



Group generator for mirror symmetry operator for 4-port structure:

$$F = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

S-matrix must commute with F: $F \cdot S = S \cdot F \Rightarrow \begin{bmatrix} S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \end{bmatrix} = \begin{bmatrix} S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{2,2} & S_{1,2} & S_{2,4} & S_{2,3} \\ S_{2,3} & S_{1,3} & S_{3,4} & S_{3,3} \\ S_{2,4} & S_{1,4} & S_{4,4} & S_{3,4} \end{bmatrix}$

It means that: $S_{2,2} = S_{1,1}, S_{2,3} = S_{1,4}$
$S_{2,4} = S_{1,3},\ S_{4,4} = S_{3,3}$

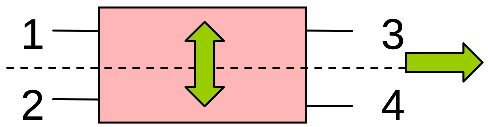
Final S-matrix of reciprocal symmetrical 4-port:
Holds for mirror or axial symmetry with the plane or axis along the propagation direction

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{1,3} & S_{1,4} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{1,3} & S_{3,4} & S_{3,3} \end{bmatrix}$$

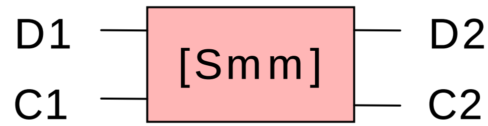
only 6 independent parameters

Mode transformation in reciprocal 4-port with geometrical mirror symmetry

Terminal space



Mixed-mode space



No mode transformation!

$$S = \begin{bmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{1,1} & S_{1,4} & S_{1,3} \\ S_{1,3} & S_{1,4} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{1,3} & S_{3,4} & S_{3,3} \end{bmatrix}$$

$$Smm = \begin{bmatrix} S_{D1,D1} & S_{D1,D2} & 0 & 0 \\ S_{D1,D2} & S_{D2,D2} & 0 & 0 \\ 0 & 0 & S_{C1,C1} & S_{C1,C2} \\ 0 & 0 & S_{C1,C2} & S_{C2,C2} \end{bmatrix}$$

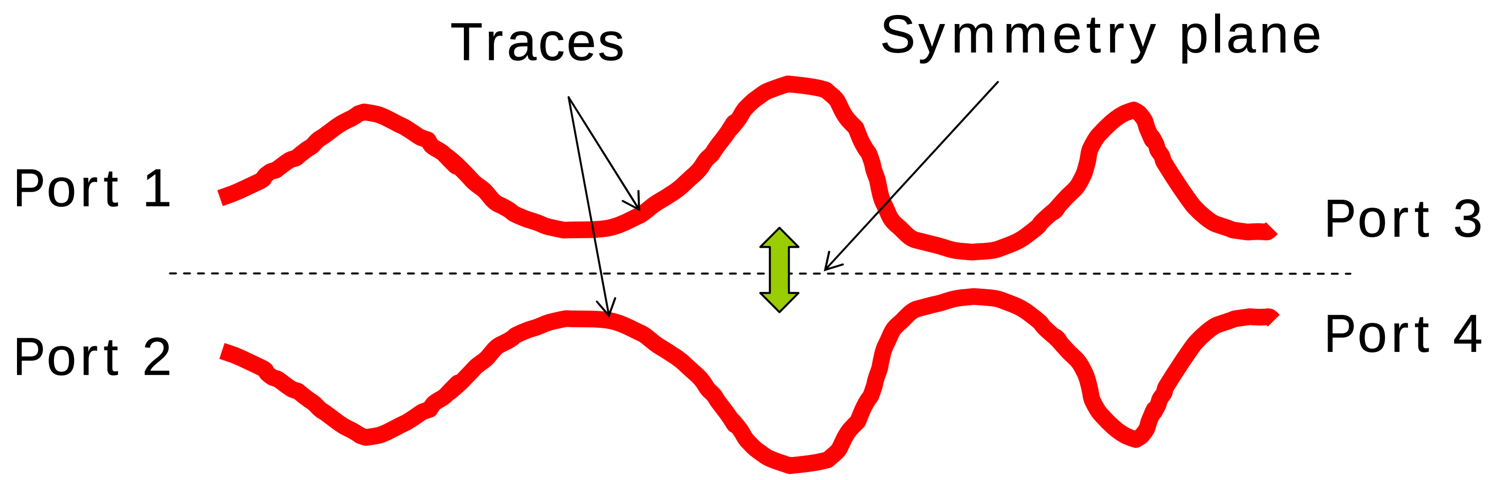
$$S_{2,2} = S_{1,1}, S_{2,3} = S_{1,4}$$
$$S_{2,4} = S_{1,3},\ S_{4,4} = S_{3,3}$$

Mode Transformation Terms are Zeroes!

$$S_{D1,C1} = 0.5 \cdot \left(S_{1,1} - S_{2,2} \right) = 0$$
$$S_{D1,C2} = 0.5 \cdot \left(S_{1,3} - S_{2,3} + S_{1,4} - S_{2,4} \right) = 0$$
$$S_{D2,C1} = 0.5 \cdot \left(S_{1,3} - S_{1,4} + S_{2,3} - S_{2,4} \right) = 0$$
$$S_{D2,C2} = 0.5 \cdot \left(S_{3,3} - S_{4,4} \right) = 0$$

NO Mode Transformation Condition

- Mirror symmetry about the plane along the interconnects is the necessary and sufficient condition of no mode transformation



NO TRANSFORMATION from Differential to Common mode and back – follows from the symmetry property

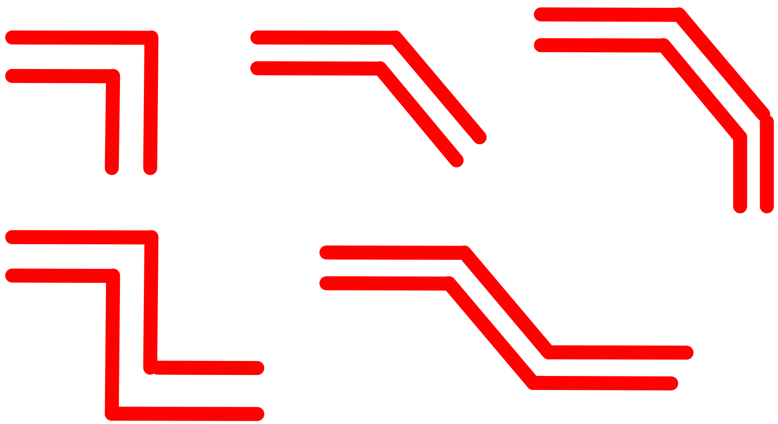
Rotational symmetry about the axis along the interconnect is another case that is less interesting for practical applications

Typical interconnect elements that cause mode transformations

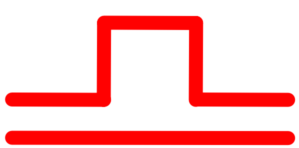
- All share one property – no symmetry of type discussed above

Can be simulated locally:

Bends (single and dual):

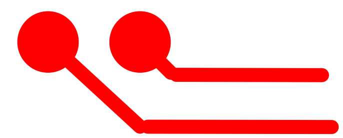


Bypass or “length equalization” elements as shown:



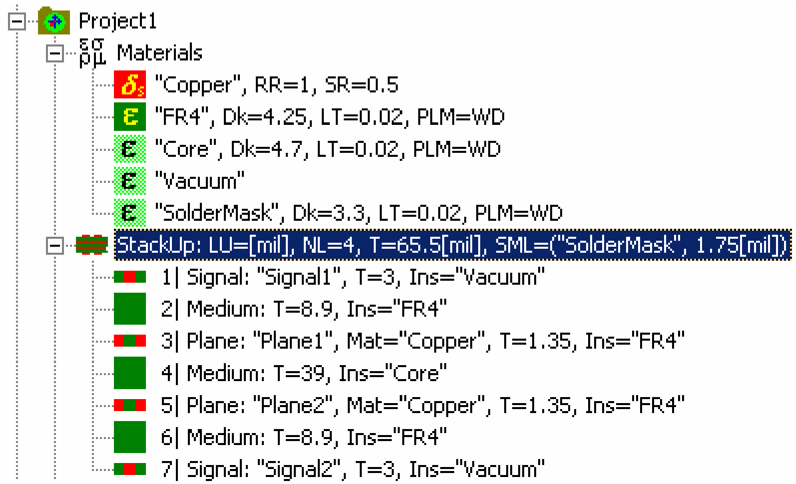
May require board-level simulation to capture common mode behavior (hybrid or full-wave):

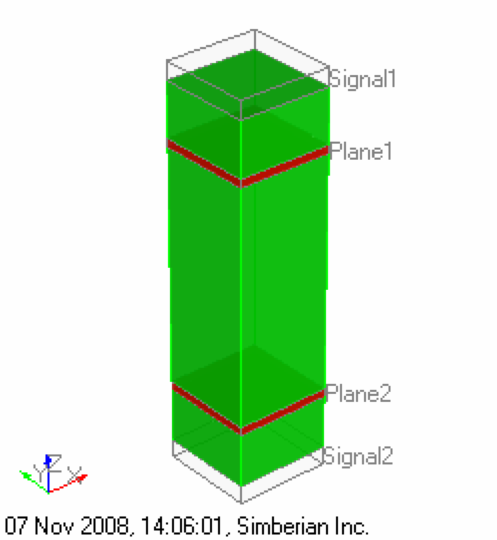
Non-symmetrical break-out from vias:



With stitching vias between all reference planes of the connected lines – can be simulated locally (conditional on the distance between vias)

Double bend in micro-strip line: Materials and Stackup

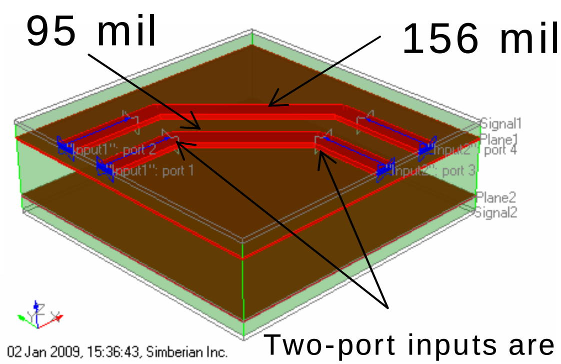




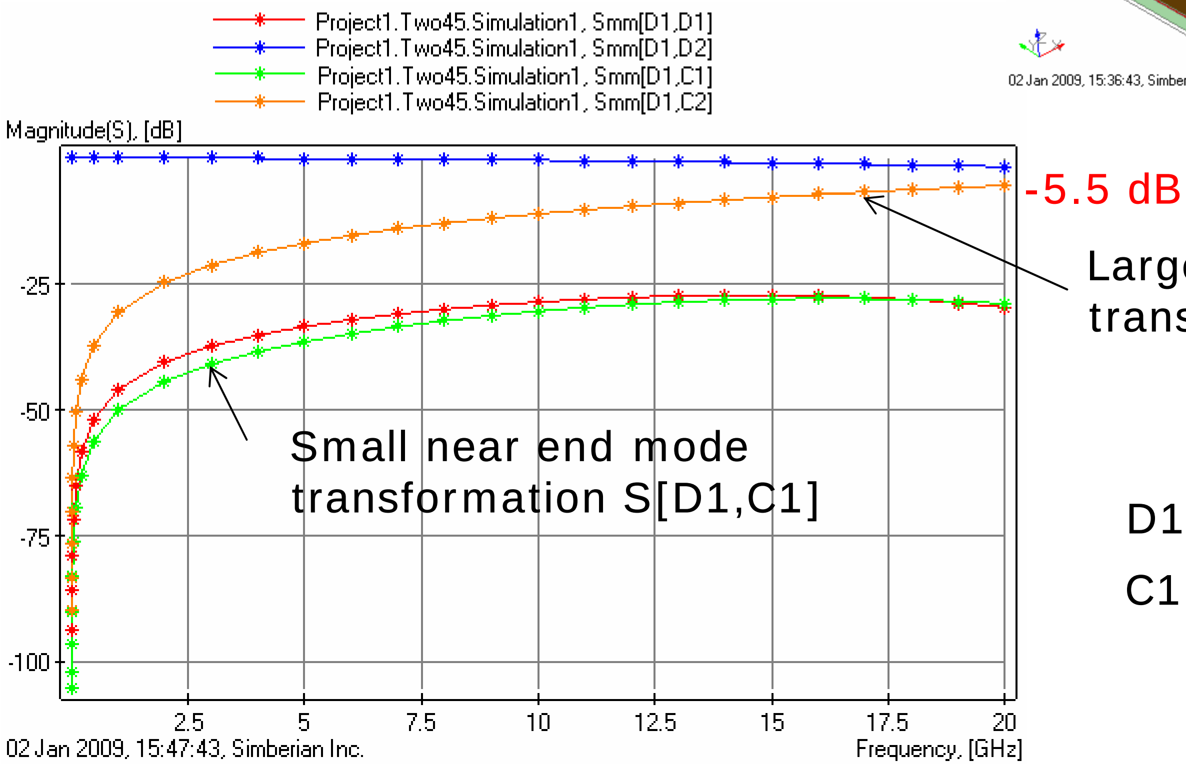
- **Materials**:
  - Copper bulk resistivity 1.724e-8 Ohm meters, roughness 0.5 um (roughness factor 2)
  - Solder mask: DK=3.3, LT=0.02
  - FR-4 core dielectric: DK=4.7, LT=0.02 @ 1 GHz
  - FR-4 dielectric between signal and plane layers: DK=4.25, LT=0.02 @ 1 GHz
  - All dielectrics are modeled with the Wideband Debye model

Mode transformation at micro-strip line bend

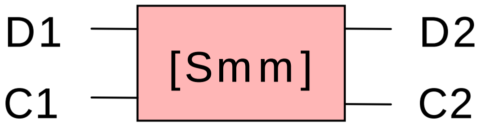
Composed of two 45-deg bends
Strip width 15 mil, separation 22 mil
Mode transformation due to non-symmetry



Two-port inputs are de-embedded and S-parameters phase reference planes are shifted to these planes

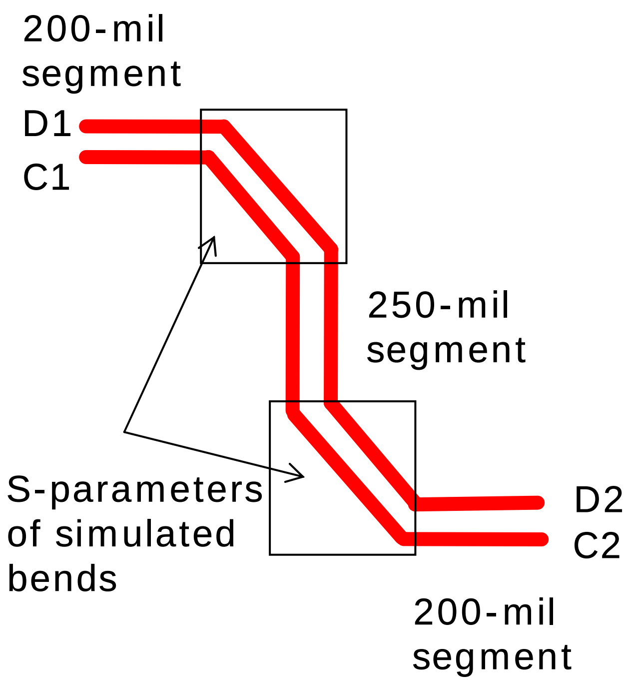


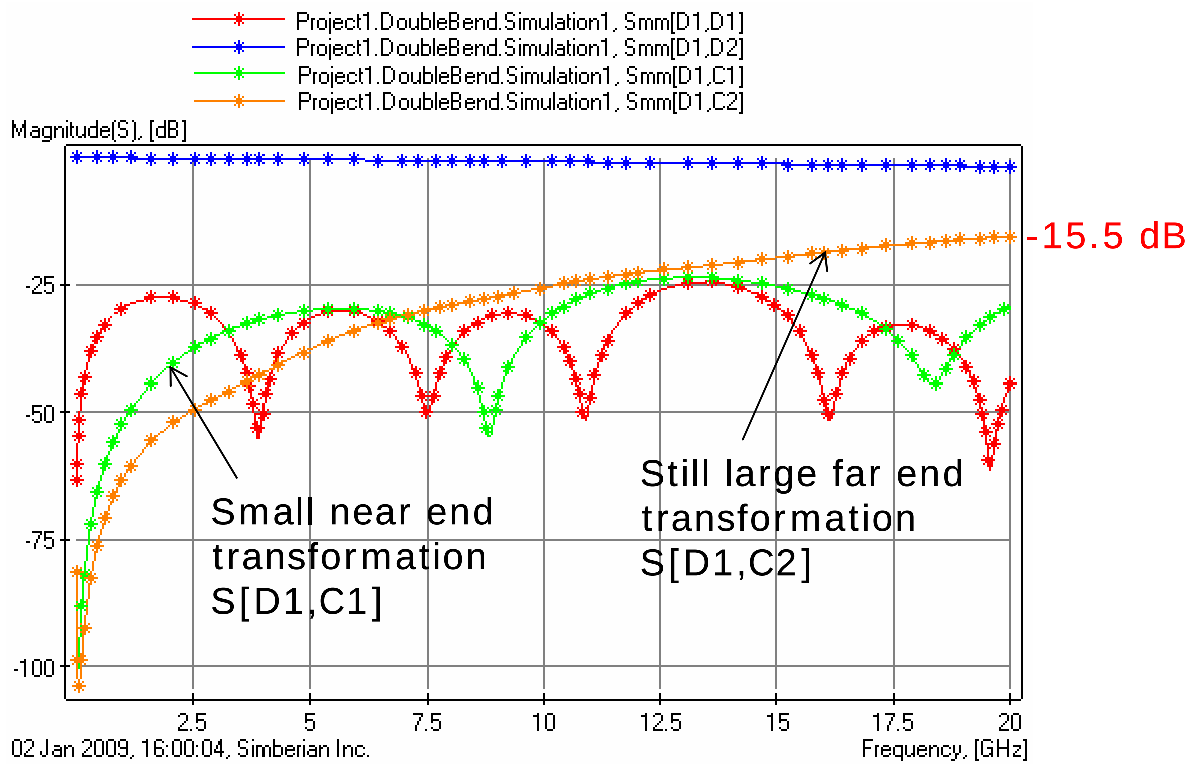
Large far end mode transformation S[D1,C2]



Can we compensate the transformation?

- By using reversed bend to match the length of the traces?



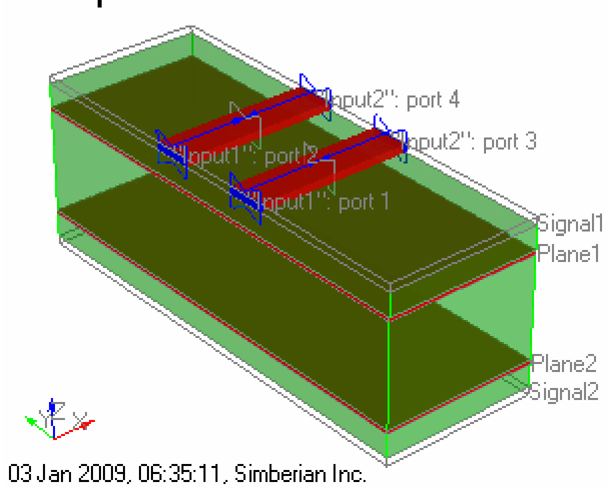


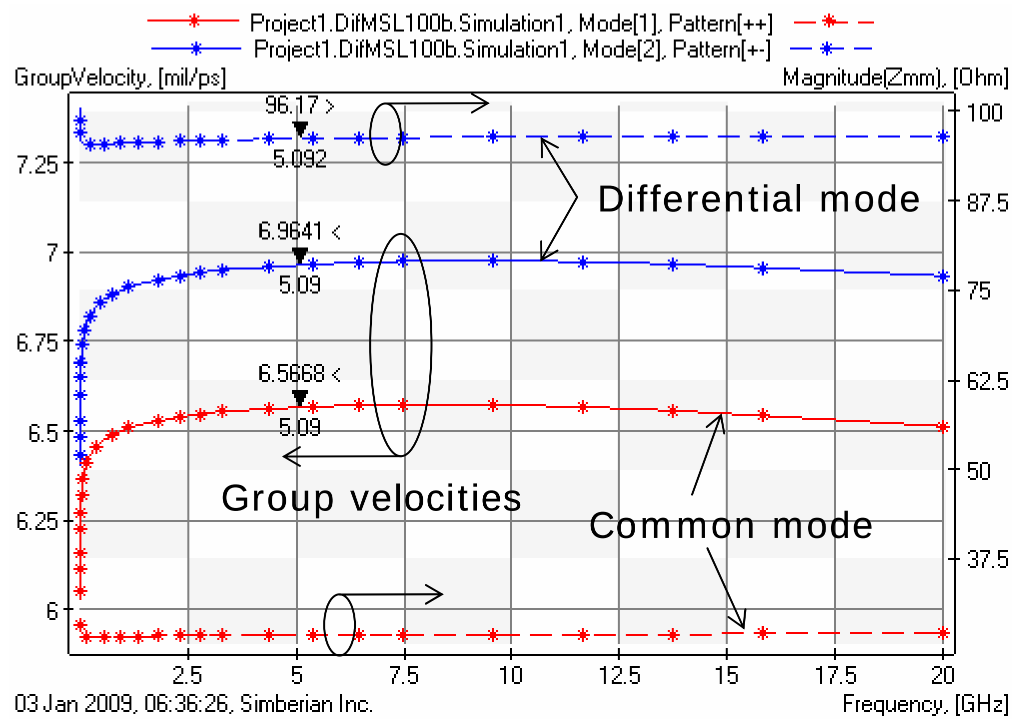
Far end transformation has been reduced by 10 dB, but did not disappear even with ideal match of the trace lengths!

What is the reason of the transformation in case with dual bends?

- Difference in the propagation velocities of differential and common modes in micro-strip line:
  - Difference in the group velocities is about 6% over the frequency band

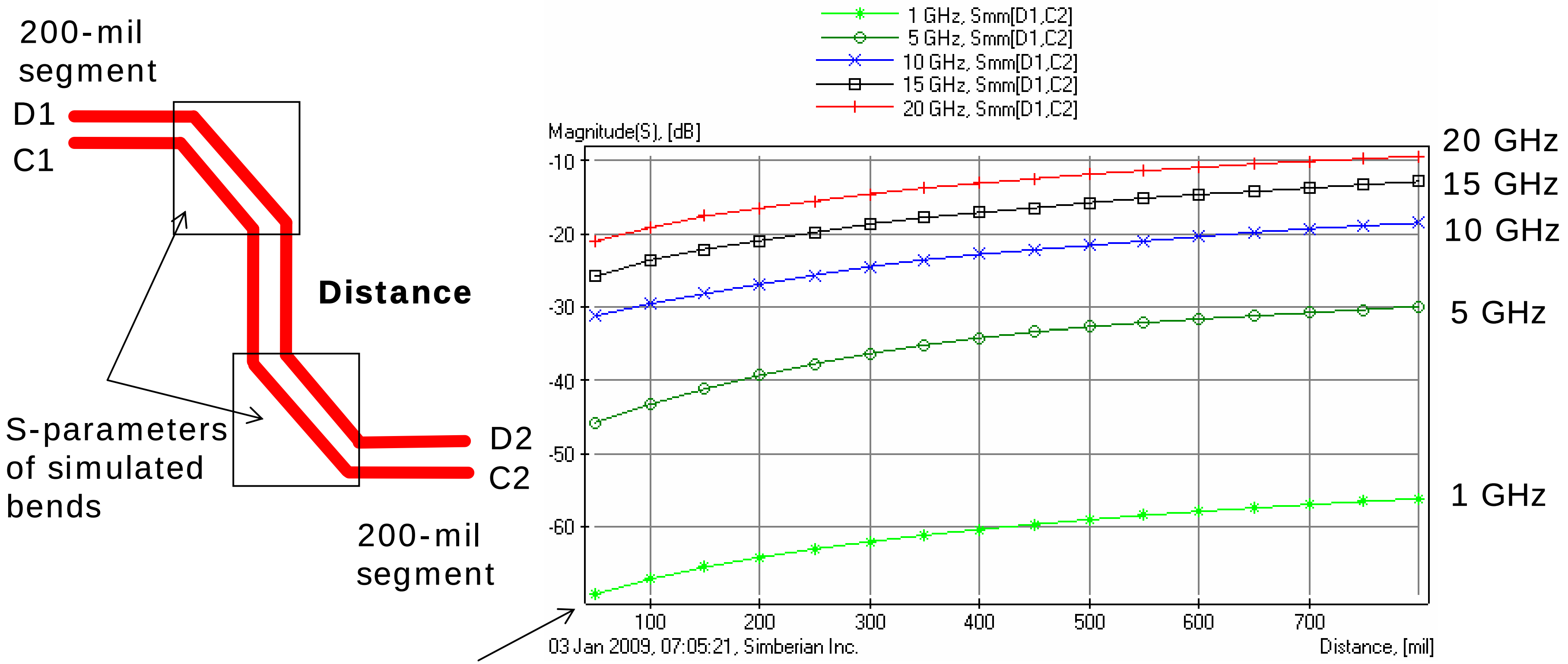
Strip width 15 mil, separation 22 mil





What if we move bends closer?

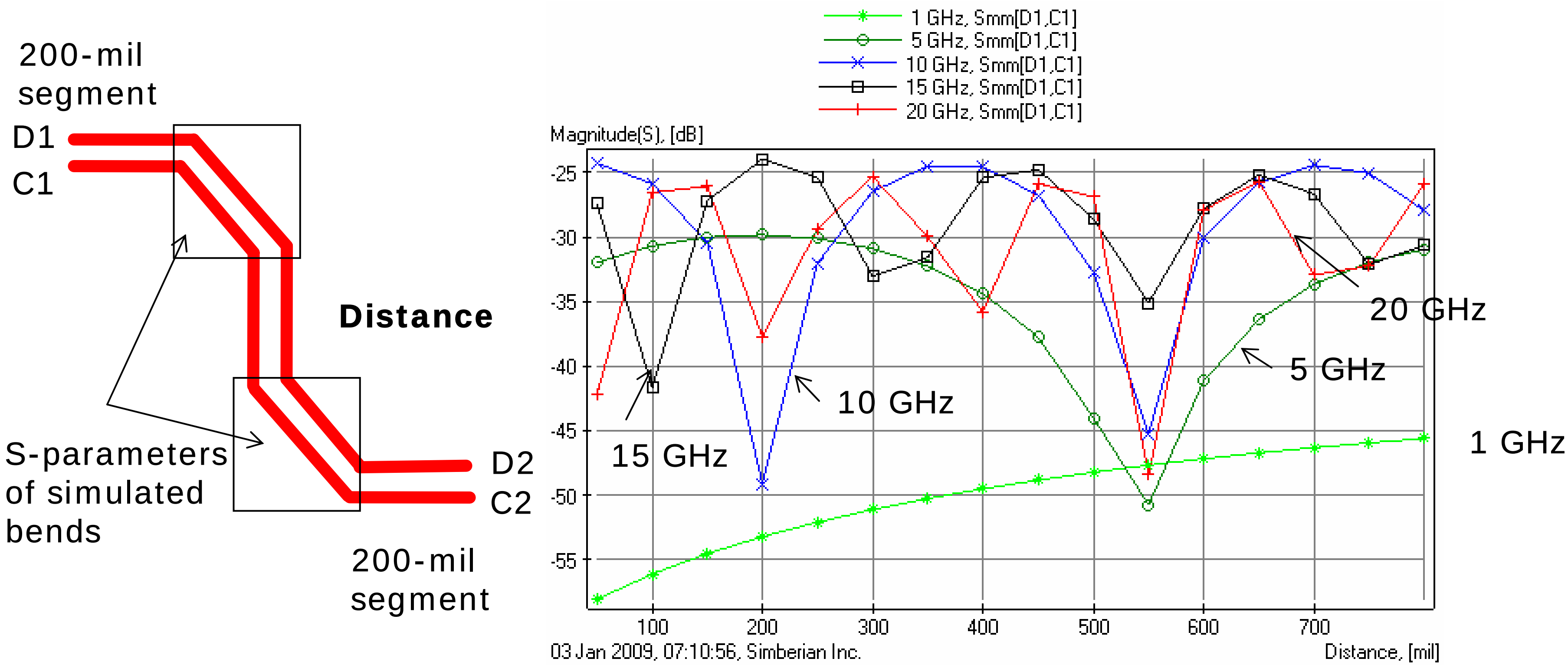
- Parametric sweep with the Distance between two bends as a parameter allows us to investigate this scenario



The smaller the Distance between the bends, the smaller the far end mode transformation coefficient S[D1,C2]

What about the near end mode transformation coefficient?

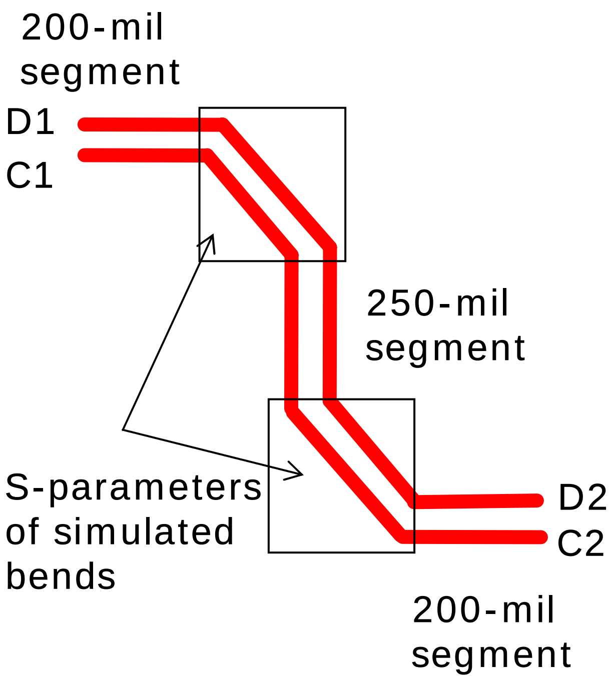
- The Distance between two bends does not have much effect on the maximal value of the near end mode transformation coefficient

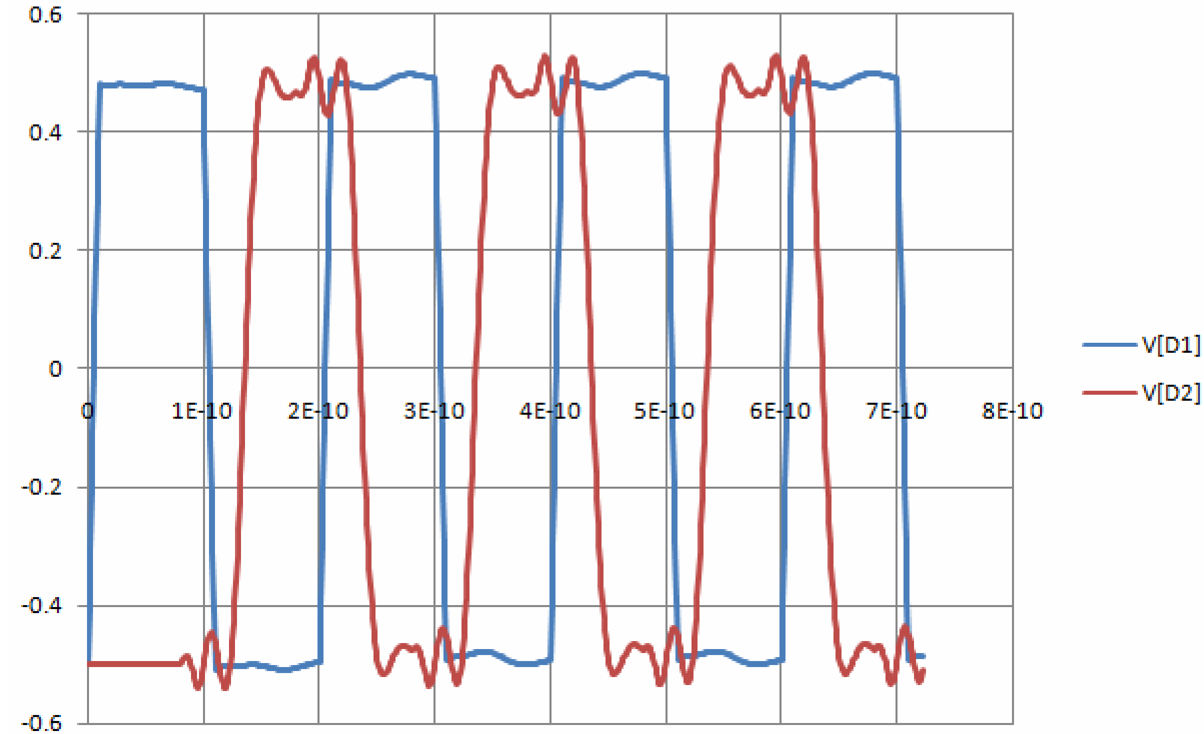


Though, the level of S[D1,C1] is relatively small (below -20 dB) due to 45-degree section used in each bend

Effect of mode transformation on signal degradation in time domain

- 10 Gbps NRZ bipolar pulse train with 10 ps rise and fall time and 1 V magnitude, 100 Ohm termination for differential mode and 25 Ohm for the common mode

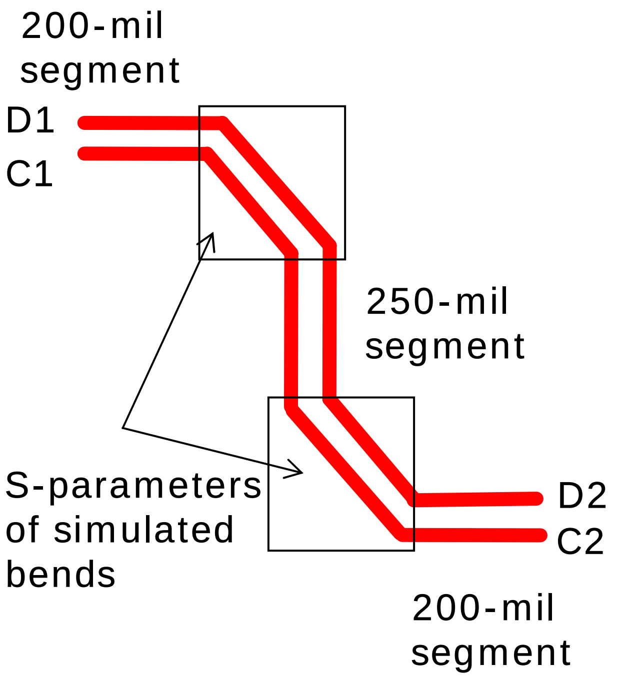


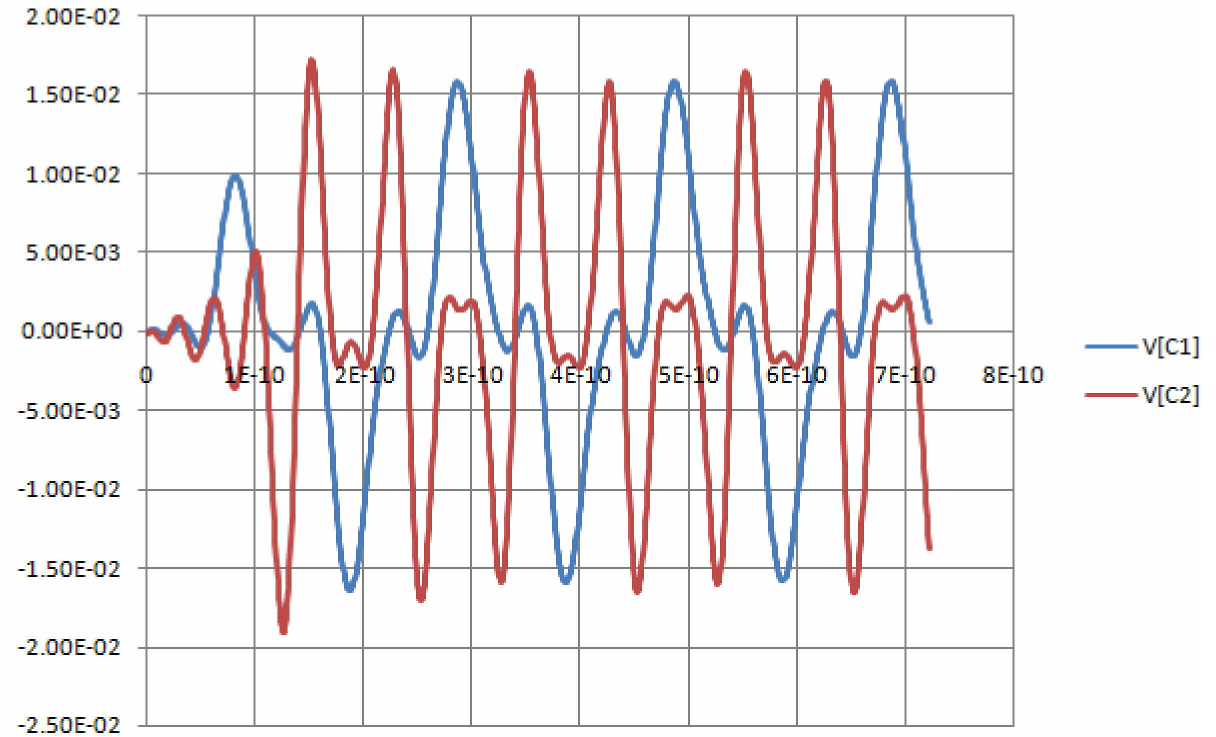


Acceptable signal degradation can be observed - partially due to the mismatch of the source (100 Ohm) and the differential mode (about 96 Ohm) – almost no skew!

Possible effect of mode transformation on EMI

- 10 Gbps NRZ bipolar pulse train with 10 ps rise and fall time and 1 V magnitude, 100 Ohm termination for differential mode and 25 Ohm for the common mode

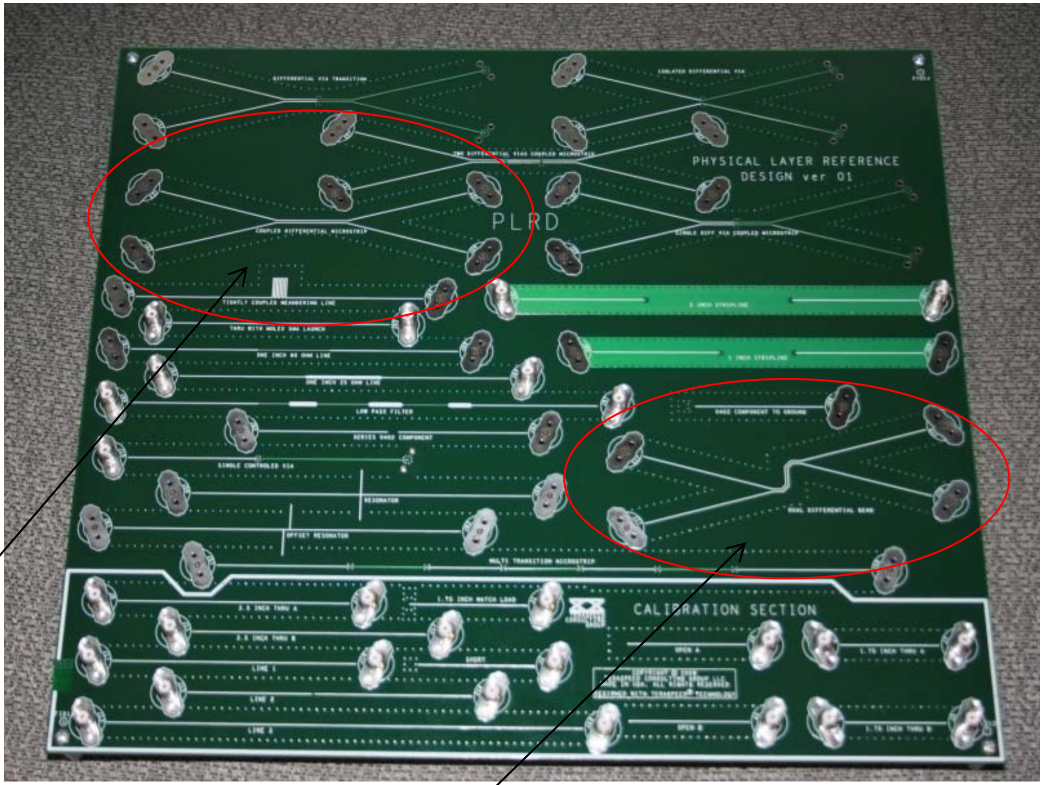




Without termination and with some other favorable conditions 15 mV injected into common mode may cause radiation (EMI problem)

Experimental validation

- PLRD-1 low cost FR4 board created and independently investigated by Teraspeed Consulting Group www.teraspeed.com
- Stackup is the same as in the previous numerical examples
- All structures are equipped with optimized SMA connectors and investigated from 300 KHz to 20 GHz

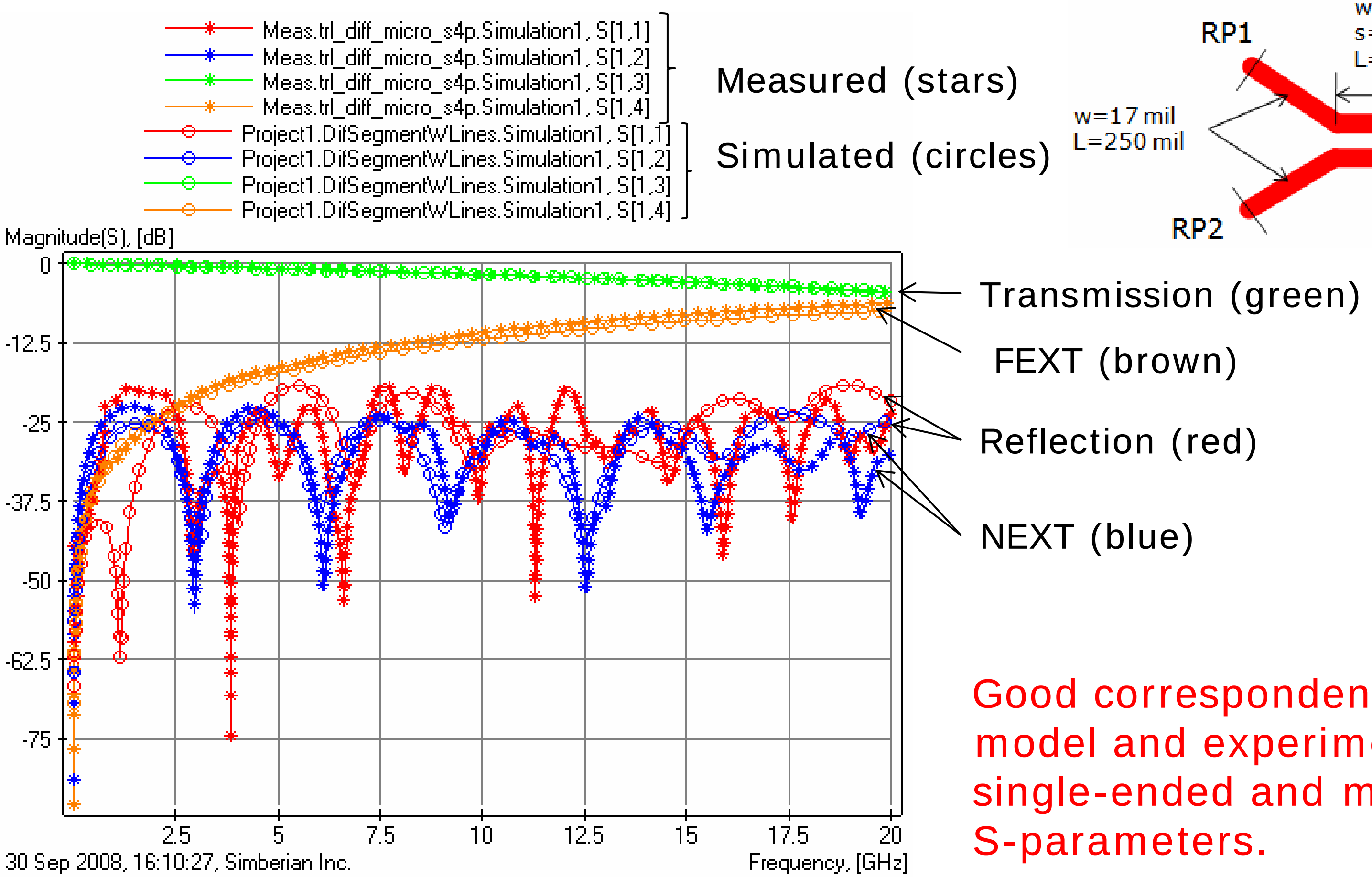


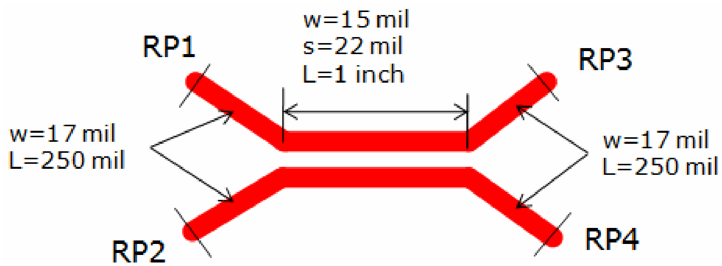
Segment of differential line (symmetrical structure)

Differential dual bend (non-symmetrical structure)

Differential line segment: Correspondence of measured and simulated results

- Magnitudes of single-ended S-parameters (1 row)

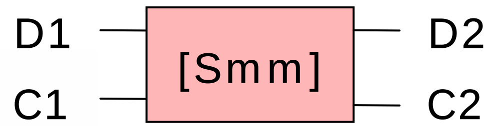


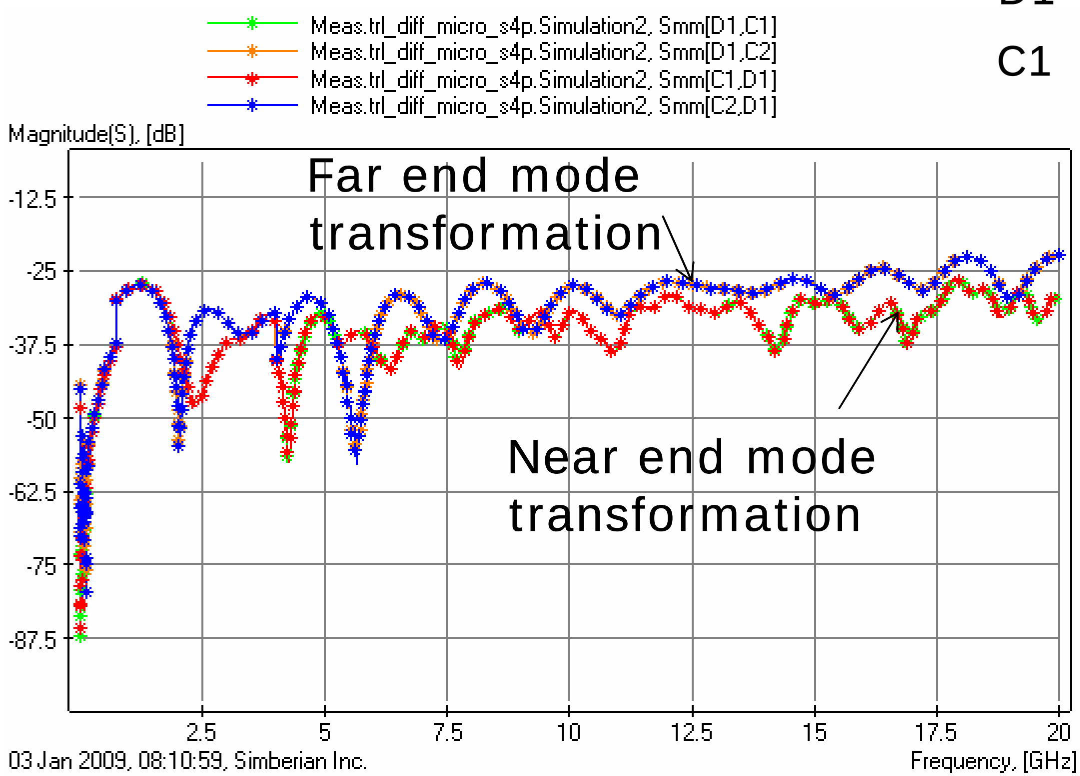


Good correspondence of the model and experiment both for single-ended and mixed-mode S-parameters.

Mode transformation in the differential line segment

- Numerical model predicts zero mode transformation due to the mirror symmetry about the plane along the wave propagation direction



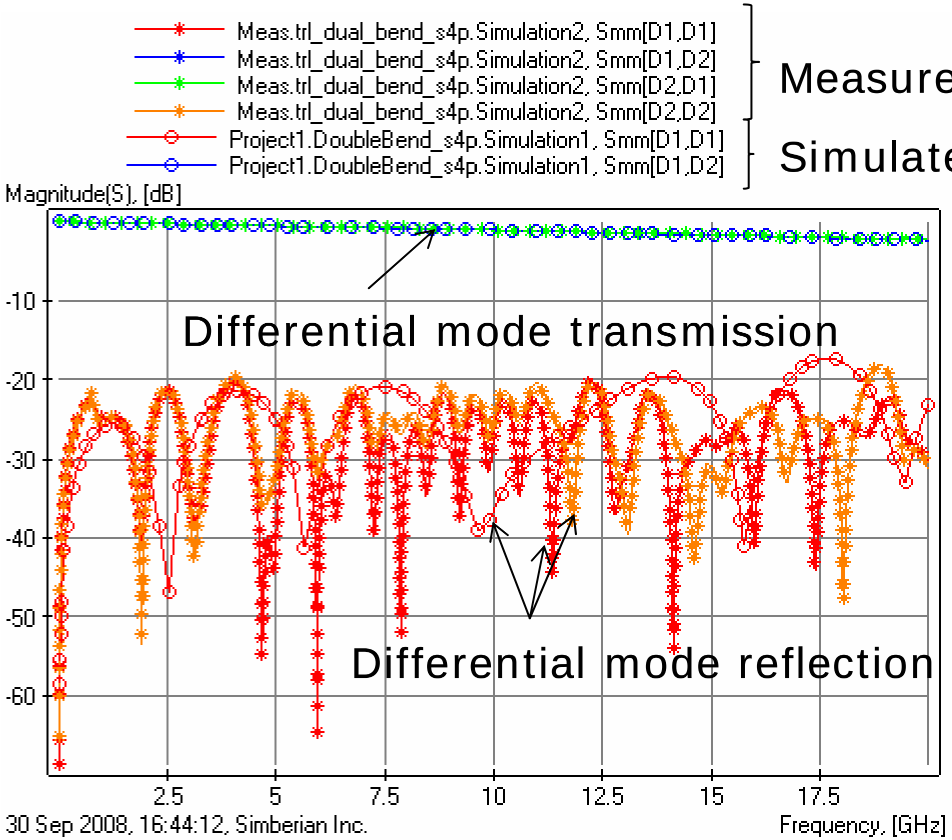


In reality, non-symmetry of connectors, glass fiber in dielectric and trace manufacturing tolerances cause small mode transformations!

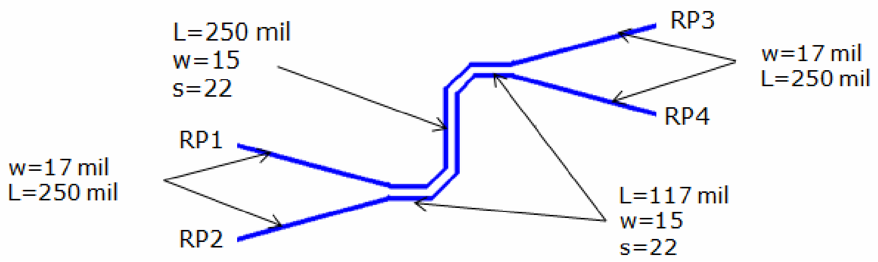
Any optimization of mode transformation below this floor level (-25 dB in that case) does not make sense.

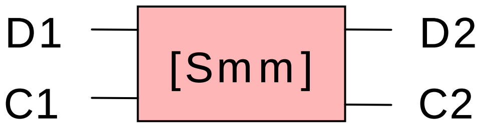
Differential bends: Comparison with de-embedded measurement results

- Magnitudes of mixed-mode S-parameters (DD block)



Good correspondence!

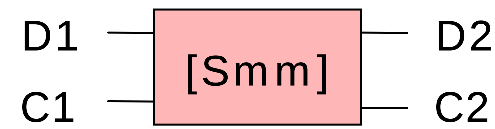


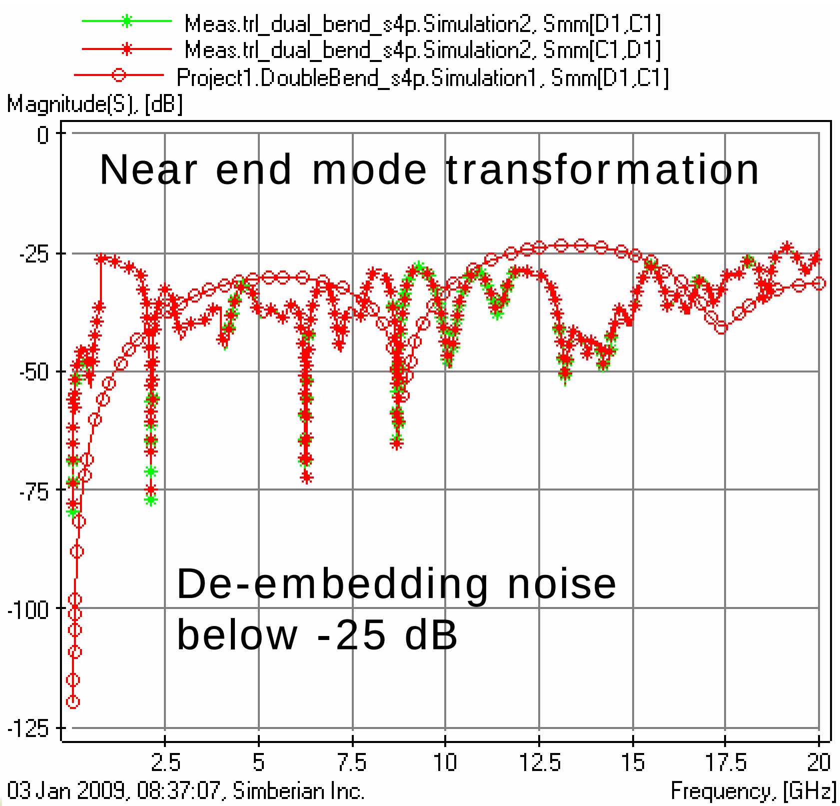


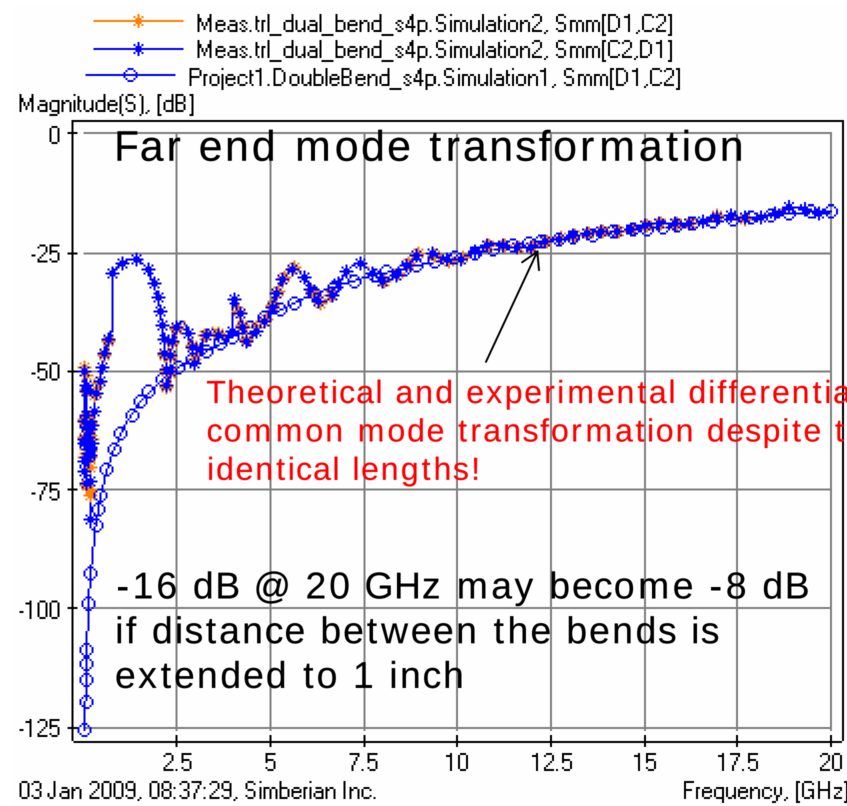
Differential bends: Mode transformation

- Acceptable correspondence between the measurements and simulation

Measured – stars
Simulated – circles







How to minimize the mode transformation?

- Reduce size of the bends to minimize both far and near end mode transformation
- Use dual or complimentary discontinuities with forward and reversed mode transformation as close to each other as possible to minimize far end mode transformation in micro-strip channels
- Use strip line structure with equal common and differential mode propagation velocity to reduce far end mode transformation
  - Disadvantages of such configuration are via-hole transitions to get to the strip layer and stitching vias for both reference planes for possibility to predict the common mode behavior
- See more practical examples in Simberian App Note #2009_01 available at www.simberian.com/AppNotes.php

Conclusion

- Transformation of differential mode to common mode in interconnects is unavoidable if structures without the mirror symmetry such as bends are used
- Amount of energy transformed into common modes at the bends can be effectively estimated with localized full-wave electromagnetic analysis and S-parameters in the mixed-mode space
- Configurations and patterns that minimize the transformation can be derived on the base of the numerical investigation of interconnects
- Even structures with the mirror symmetry by design may have mode transformation due to non-symmetries introduced by dielectric structure and manufacturing tolerances – the transformation value can be used as the floor for the mode transformation optimization
- Transformation may have minor effect on signal quality (signal integrity), but may have more serious consequences on EMI if common mode is not appropriately terminated